Search for high mass SM Higgs at the Tevatron

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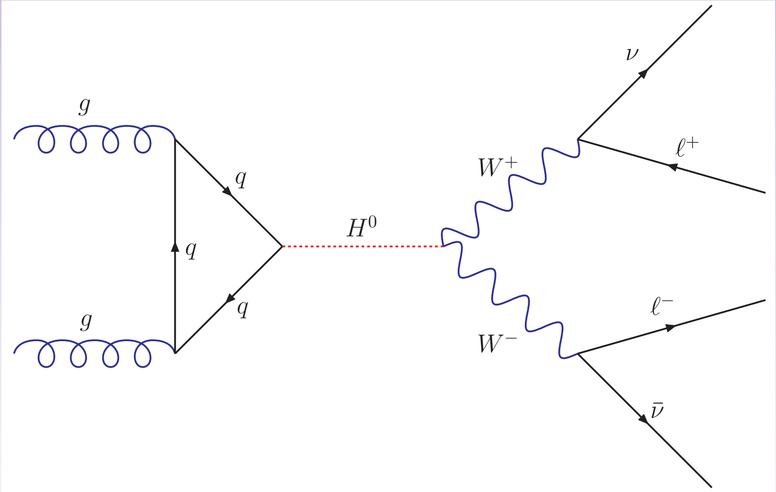
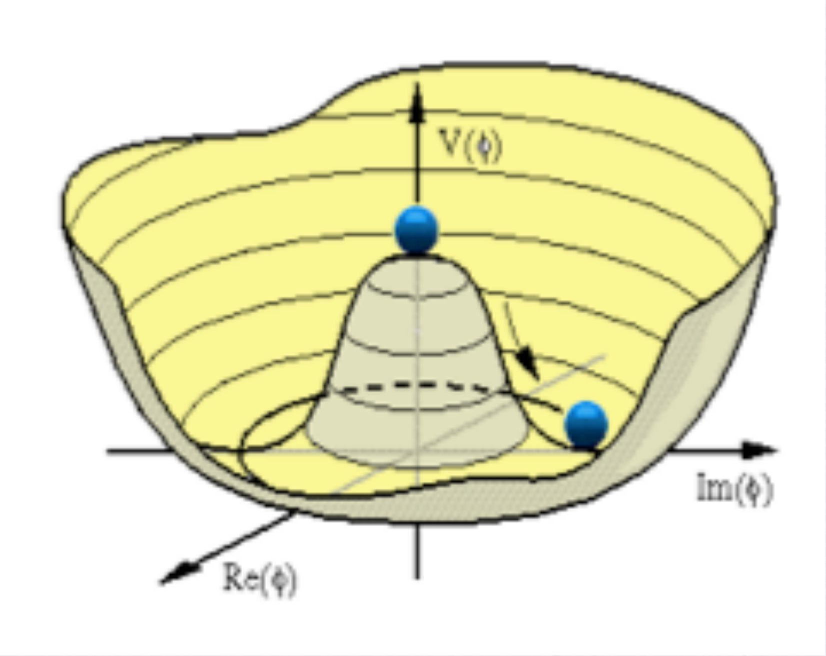
Outline:

- ✓ Motivation
- ✓ Approach
- ✓ CDF Analysis
- ✓ D0 Analysis
- ✓ Combined Limits
- ✓ Future Prospects



Higgs Phenomenology

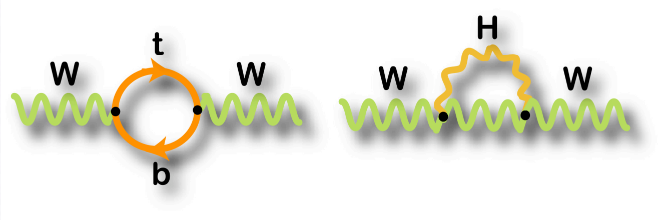
- Higgs field is a complex scalar field introduced to break the electroweak symmetry and to introduce mass terms in the Standard Model (SM) Lagrangian
- Neutral, spin 0 Higgs Boson must be found to complete SM picture
- Higgs mass is a parameter of the theory

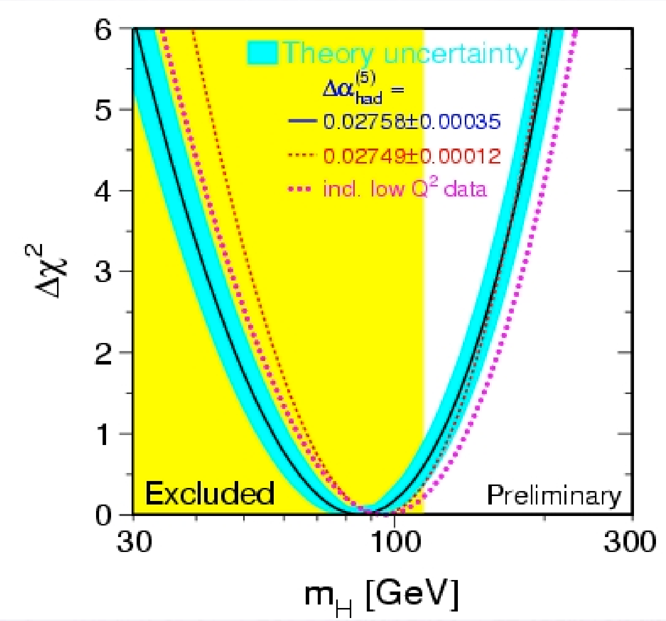


Constraints on Higgs mass

- Precision Fit of electroweak precision data, including top quark and W masses
- best fit Higgs mass = 76 + 33 - 24 GeV

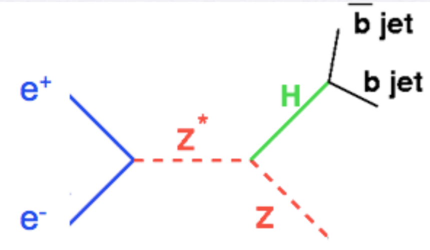
➡ **m_H < 144 GeV at 95% CL**





Direct Search Limit:

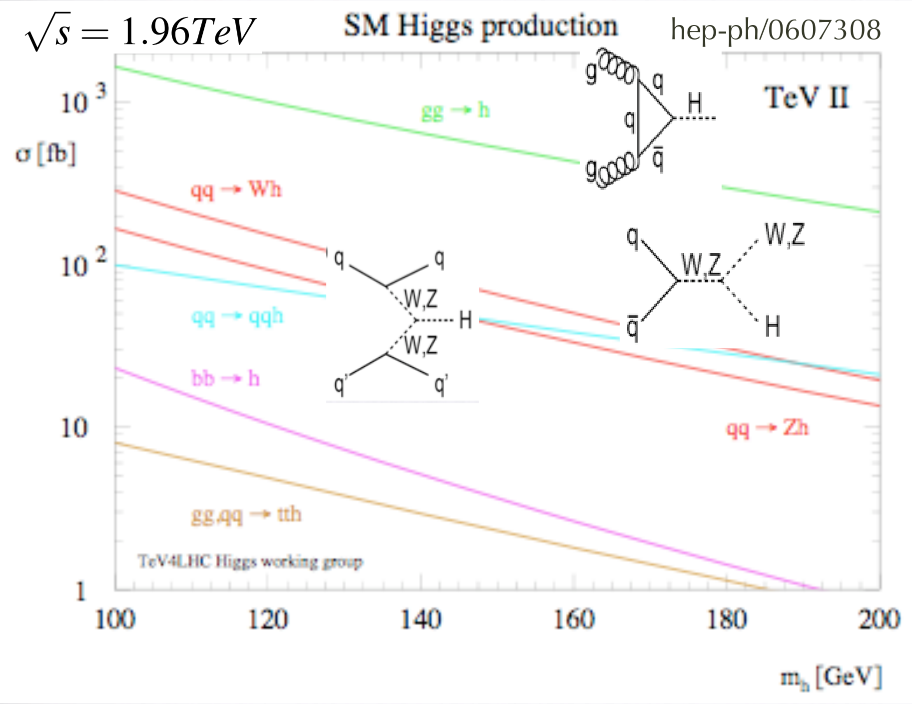
$m_H \geq 114.4$ GeV @ 95% CL



Combined direct/indirect limit:

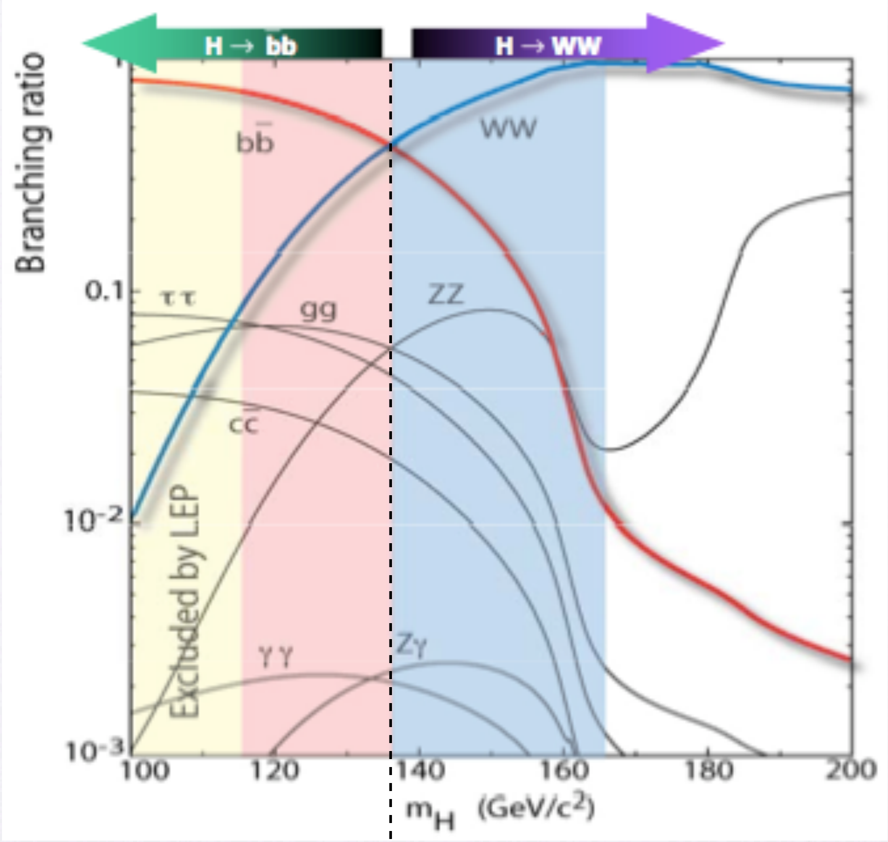
m_H < 182

Higgs Production & Decay



Production through gluon fusion,
Higgsstrahlung or vector boson fusion

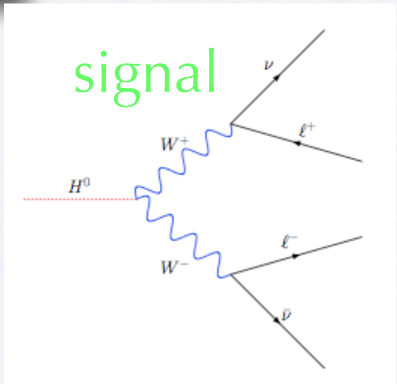
Higgs decays to pairs of fermions or bosons, depending on available phase space to produce real particles.



high mass region

For maximal signal significance:
- Higgsstrahlung or "associated production" searches at low mass
- gluon fusion searches at high mass

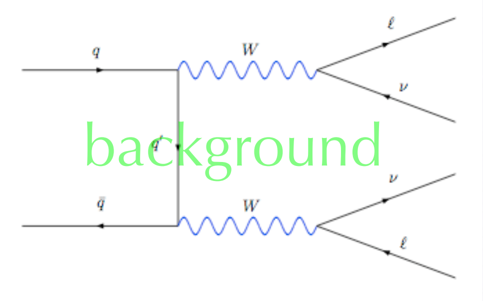
$H^0 \rightarrow WW^* \rightarrow l^\pm \nu l^\mp \nu'$



Event Signature

- 2 high p_T leptons and missing E_T

Backgrounds: Diboson (mainly WW), Drell-Yan, tt, W+jets



Analysis Approach - similar for CDF and D0

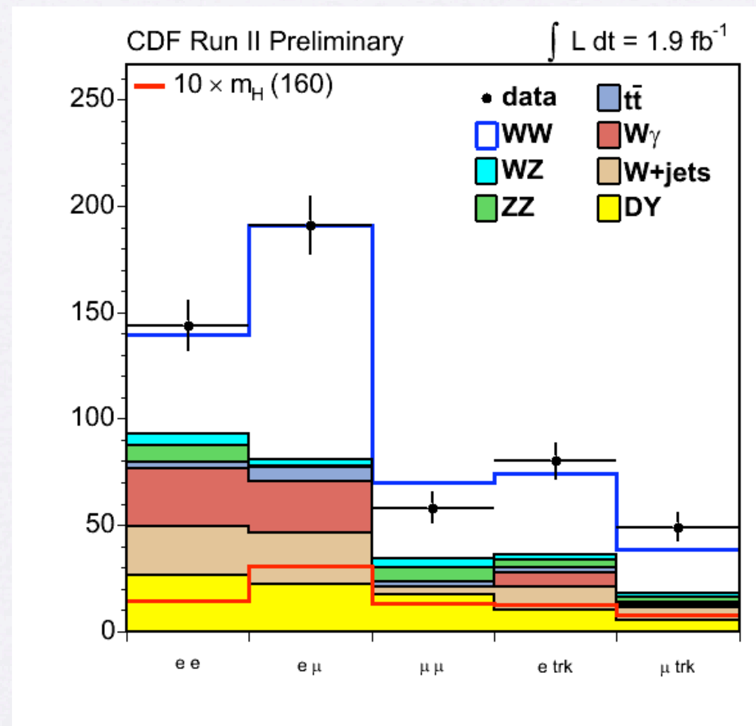
- Phase space selection
  - data are binned according to lepton flavor: $e^\pm e^\mp,\ e^\pm \mu^\mp,\ \mu^\pm \mu^\mp$
- Simulate background processes
- Normalize the backgrounds
- Analyze the data with multivariate techniques
- In the absence of signal, extract limits

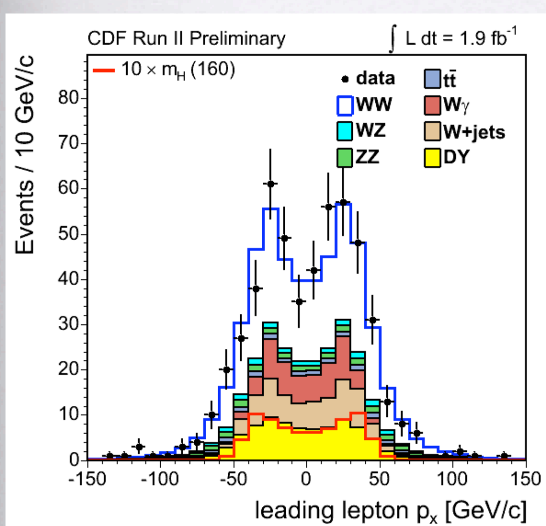
CDF Analysis

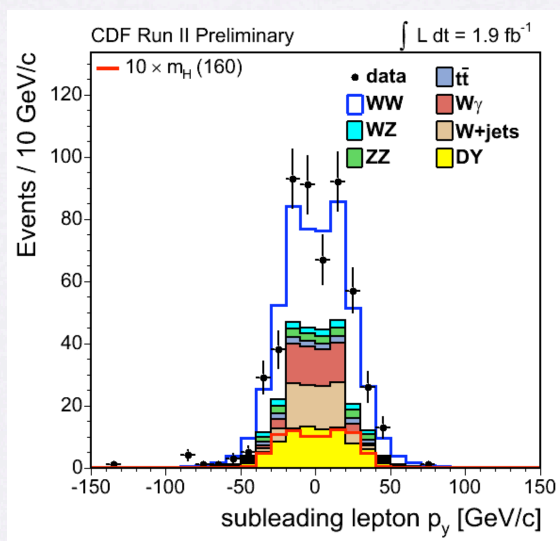
Base Selection →

$p_{T,1} > 20, p_{T,2} > 10$
$25 < \not{E}_{T,rel} = \not{E}_T \cdot \sin(\min(\pi/2, \Delta\phi(\not{E}_T, \text{lepton or jet}))$
$\not{E}_T \sqrt{\sum E_T} > 2.5$
$n_{\text{jets}} < 2\ (p_T > 15GeV)$
$m_{ll} > 16$
trilepton veto

- lepton trigger selection
- 2(4) categories of electron (muons) with opposite charge
- lepton and missing E_T cuts applied to reduce backgrounds
- event-by-event likelihood ratio discriminant constructed as final variable







Event Yields

- Background/Data yields:

Base $ll\not{E}_T$ Selection									
Category	WW	WZ	ZZ	$t\bar{t}$	DY	$W\gamma$	W+jets	Total	Data
$e\ e$	46.6	5.3	8.2	2.9	26.6	27.2	22.8	140 $\pm$12	144
$e\ \mu$	110.1	3.2	0.5	7.0	22.5	23.8	24.1	191 $\pm$17	191
$\mu\ \mu$	36.0	4.1	6.7	2.7	17.6	0.0	3.1	70 $\pm$ 6	58
e trk	37.8	2.6	3.3	2.6	10.3	6.5	10.9	74 $\pm$ 6	80
μ trk	20.6	1.6	2.3	1.5	5.3	1.1	5.8	38 $\pm$ 3	49
Total	251.0	16.9	20.9	16.8	82.2	58.5	66.6	513 $\pm$41	522

- Signal yields:

	Higgs Mass (GeV)									
Category	110	120	130	140	150	160	170	180	190	200
$e\ e$	0.1	0.3	0.6	0.9	1.2	1.4	1.4	1.1	0.8	0.6
$e\ \mu$	0.2	0.6	1.3	2.0	2.6	3.1	3.0	2.5	1.8	1.4
$\mu\ \mu$	0.1	0.2	0.5	0.8	1.1	1.3	1.3	1.0	0.7	0.6
e trk	0.0	0.2	0.4	0.7	0.9	1.2	1.2	1.0	0.7	0.6
μ trk	0.0	0.1	0.2	0.4	0.6	0.8	0.7	0.6	0.4	0.3
Total	0.4	1.3	3.0	4.8	6.4	7.8	7.6	6.2	4.4	3.5

Matrix Element in H->WW*

- idea: use LO matrix elements to calculate event probabilities
- for each event and process integrate ME over phase space, accounting for efficiency and resolution of observables

$$P_m(x_{obs}) = \frac{1}{<\sigma_m>} \int \frac{d\sigma_m^{th}(y)}{dy} \epsilon(y) G(x_{obs}, y) dy$$

ME

efficiency

resolution

- calculate likelihood ratio for each event:

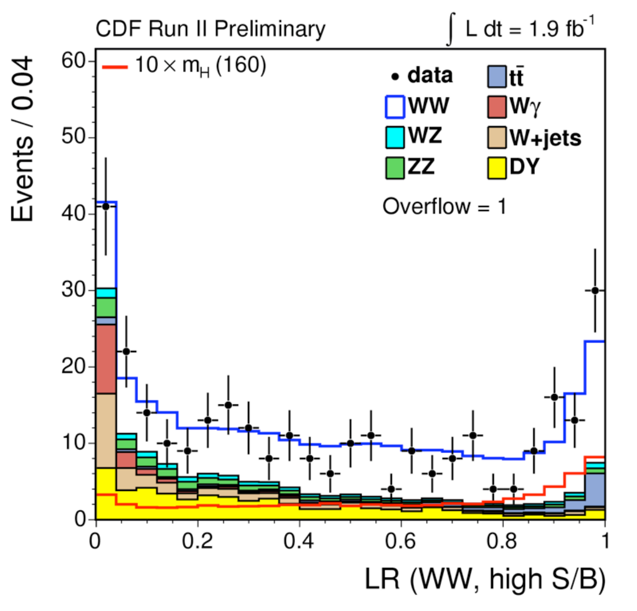
$$LR(x_{obs}) \equiv \frac{P_H(x_{obs})}{P_H(x_{obs}) + \sum_i k_i P_i(x_{obs})}$$

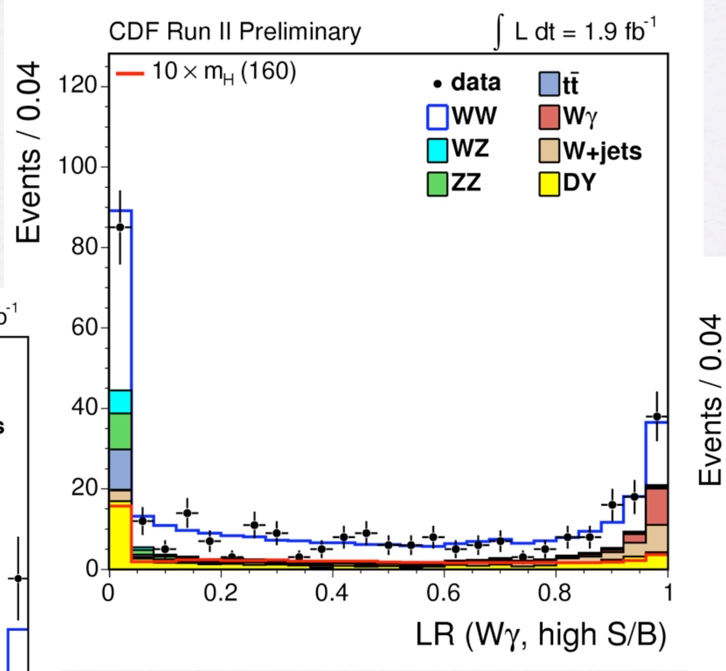
H = Higgs mass hypothesis

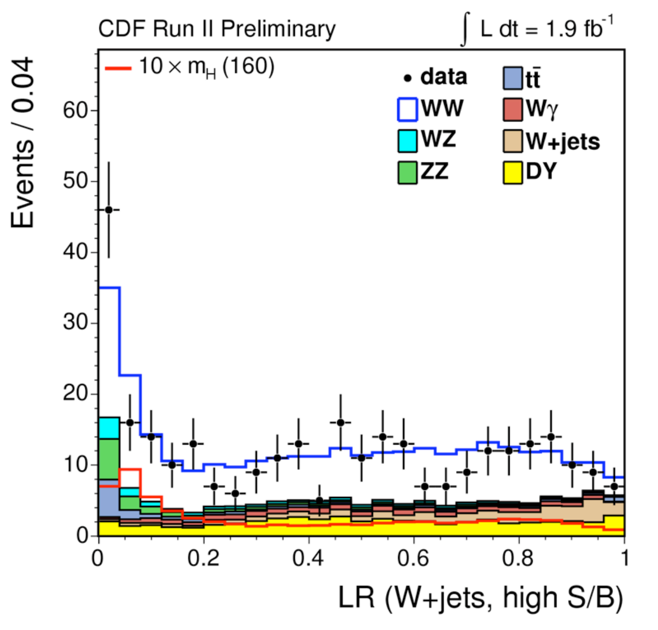
k_i = expected fraction per background

LR cross-checks

- Define LR discriminants for background processes
- Good agreement between data and expectation indicate accurate background simulation

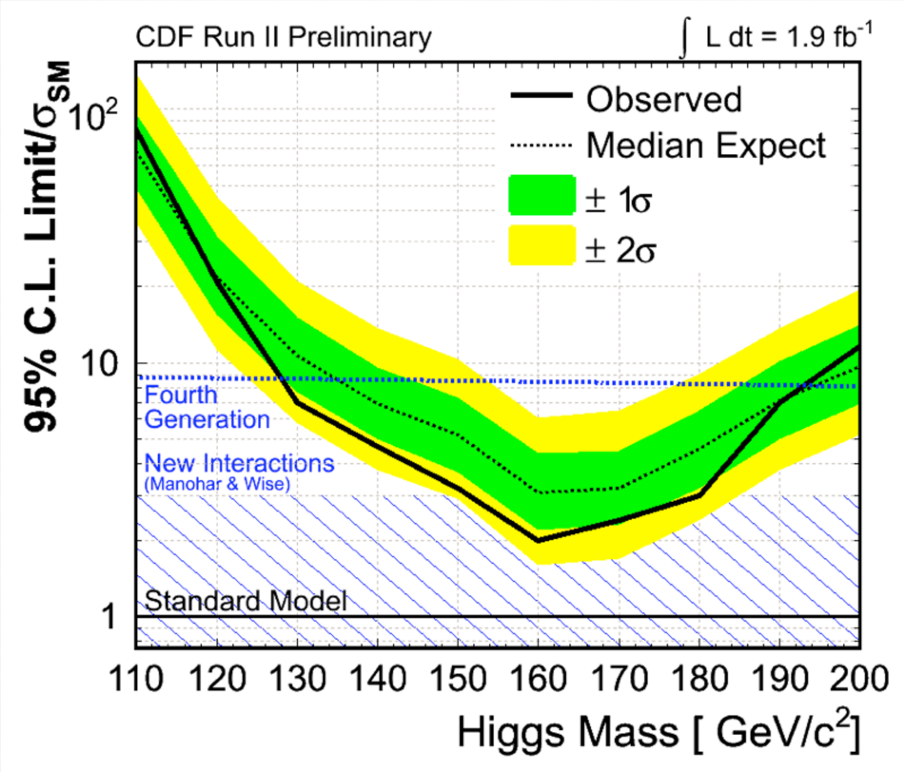


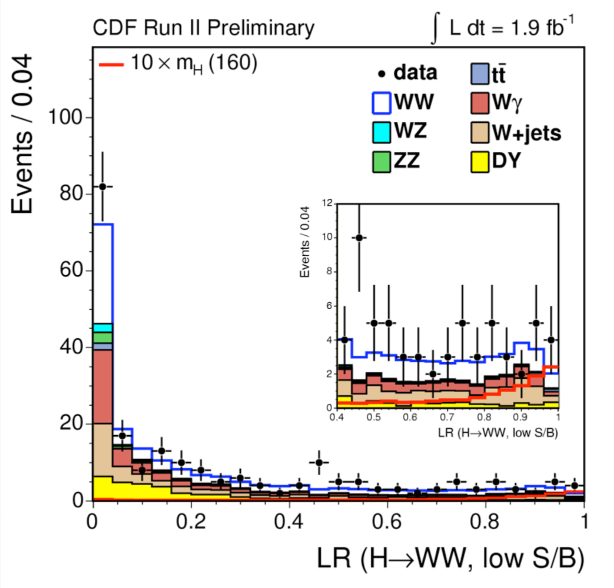


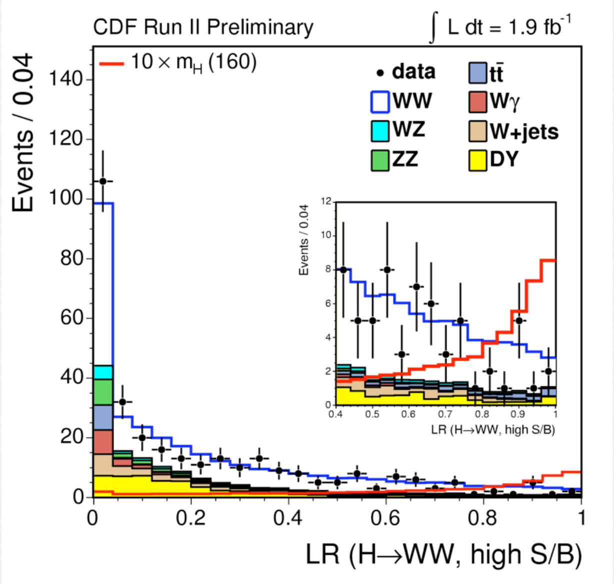


Result

- Data separated into regions of low and high S/B
- Binned maximum likelihood fit of LR discriminant used to determine limit
- $\sigma_H \times BR < 0.8$ pb @ 95% CL for m_H=160 GeV/c^2
  - ➡ Observed Limit/σ_{SM} (NNLL) ~ 2
  - ➡ Expected Limit/σ_{SM} (NNLL) ~ 3

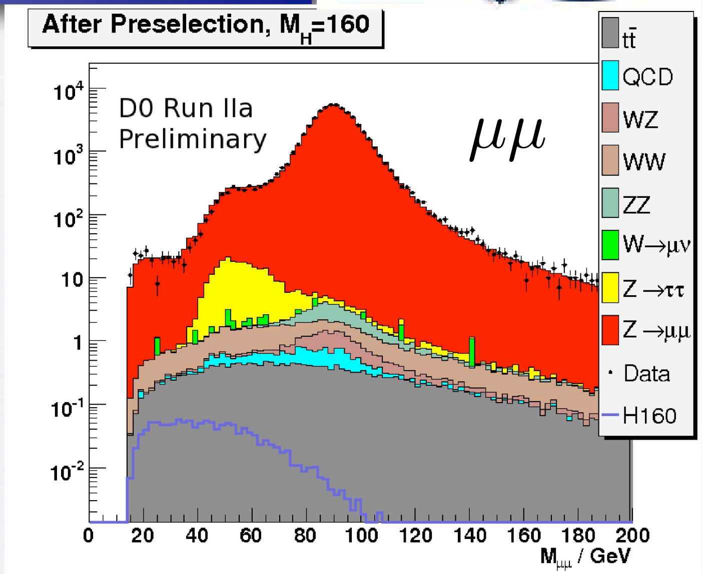


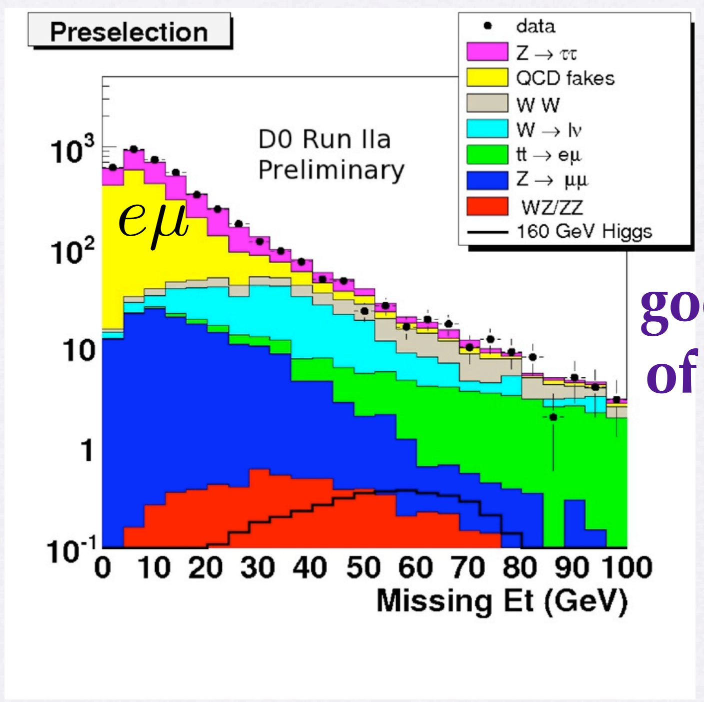




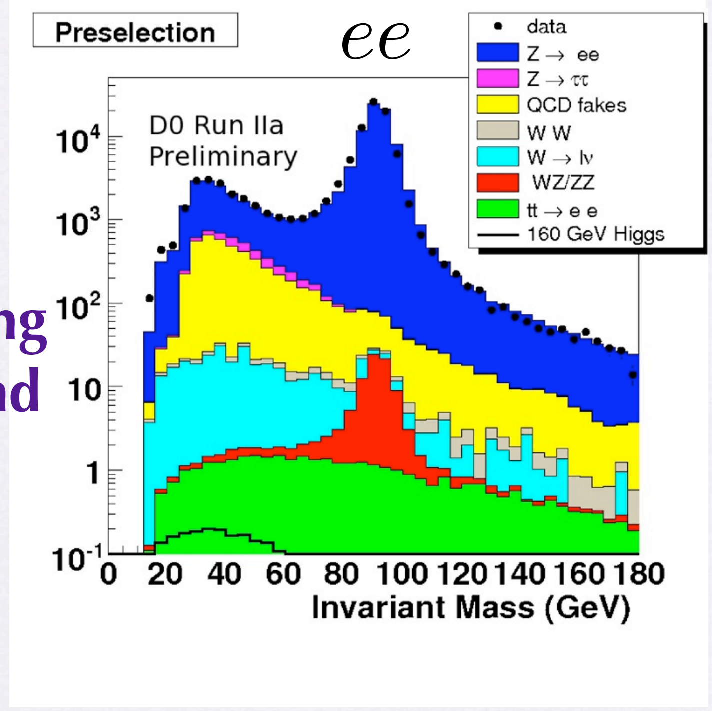
D0 Analysis

- Preselection:
  - combined single, di-lepton trigger selection ensures efficiency > 95%
  - 2 leptons with opposite charge
  - lepton p_T>10-20 GeV depending on channel, Higgs mass
  - M_{ee}, $M_{e\mu}$ ($M_{\mu\mu}$) > 15 (17) GeV
- Final selection cuts optimized for each Higgs mass separately





good modeling of background



Event Yields

Final (stringent) selection:

	$ee(1.1 fb^{-1})$	$e\mu(1.1 fb^{-1})$	$\mu\mu(1.7 fb^{-1})$
lepton ID	$p_{T,1} > 15, p_{T,2} > 10$		$p_{T,1} > 20, p_{T,2} > 10$
lepton ID	$m_{ll} > 15$, isolation		$m_{ll} > 17$, isolation
$\not{E}_T$	$\not{E}_T > 25 - 35$, scaled$(\not{E}_T) > 7$		
$m_{ll} < x$	$\min(m_H/2, 80)$	$m_H/2$	
$p_{T,1} + p_{T,2} + \not{E}_T$			$m_H/2 + 20 < x < m_H$
$m_{T,\min}(l, \not{E}_T)$	$x > 50 - 65$		$x > 30 - 45$
$H_T = \sum p_T^{\text{jet}}$	$H_T < 70$		$H_T < 50 - 60$
$\Delta\phi_{ll}$	$\Delta\phi_{ll} < 1.25 - 1.5$		

$\mu\mu$ channel:

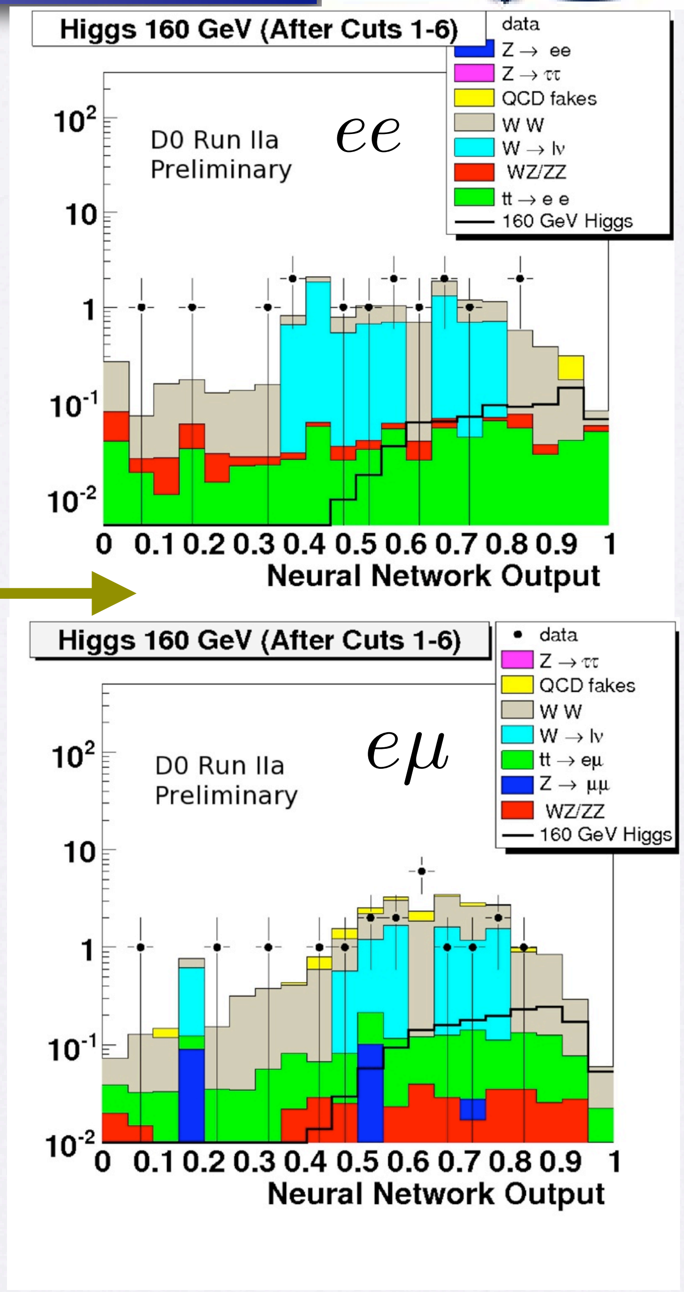
M_H (GeV)	120	140	160	180	200
$H \rightarrow W^+W^-$	0.32 ± 0.01	0.87 ± 0.01	1.29 ± 0.01	0.90 ± 0.03	0.43 ± 0.01
$Z/\gamma \rightarrow ll$	9.4 ± 0.6	6.0 ± 0.5	1.3 ± 0.2	1.5 ± 0.2	2.9 ± 0.3
Diboson (WW, WZ)	12.5 ± 0.1	14.9 ± 0.1	9.7 ± 0.1	10.7 ± 0.1	14.7 ± 0.1
$t\bar{t}$	0.4 ± 0.1	0.8 ± 0.1	0.6 ± 0.1	0.7 ± 0.1	0.7 ± 0.1
W+jet/γ	8.0 ± 1.7	3.5 ± 1.1	1.1 ± 1.1	1.0 ± 1.1	0 ± 1.7
Multi-jet	0.2 ± 0.1	0.1 ± 0.1	$0. \pm 0.$	$0. \pm 0.$	0 ± 0
Background sum	20.8 ± 1.7	25.3 ± 1.2	12.6 ± 2.0	13.8 ± 1.2	18.3 ± 1.7
Data	31	24	10	12	18

NN applied to H->WW* search

- Neural net discriminant tuned to further enhance signal and background separation
  - Event variables are inputs:

$p_{T,1}$
$p_{T,2}$
$M_{T(1,2,MET)}$
$m_{1,2}$
$\Delta\phi_{1,2}$
$\Delta\phi_{1,MET}$
$\Delta\phi_{2,MET}$
MET
$p_{T,1}+p_{T,2}+MET$

NN



  - NN trained on WW background samples, run on all backgrounds; separate optimization for each channel and Higgs mass

- Final result determined from fit to NN output

Systematic Uncertainties

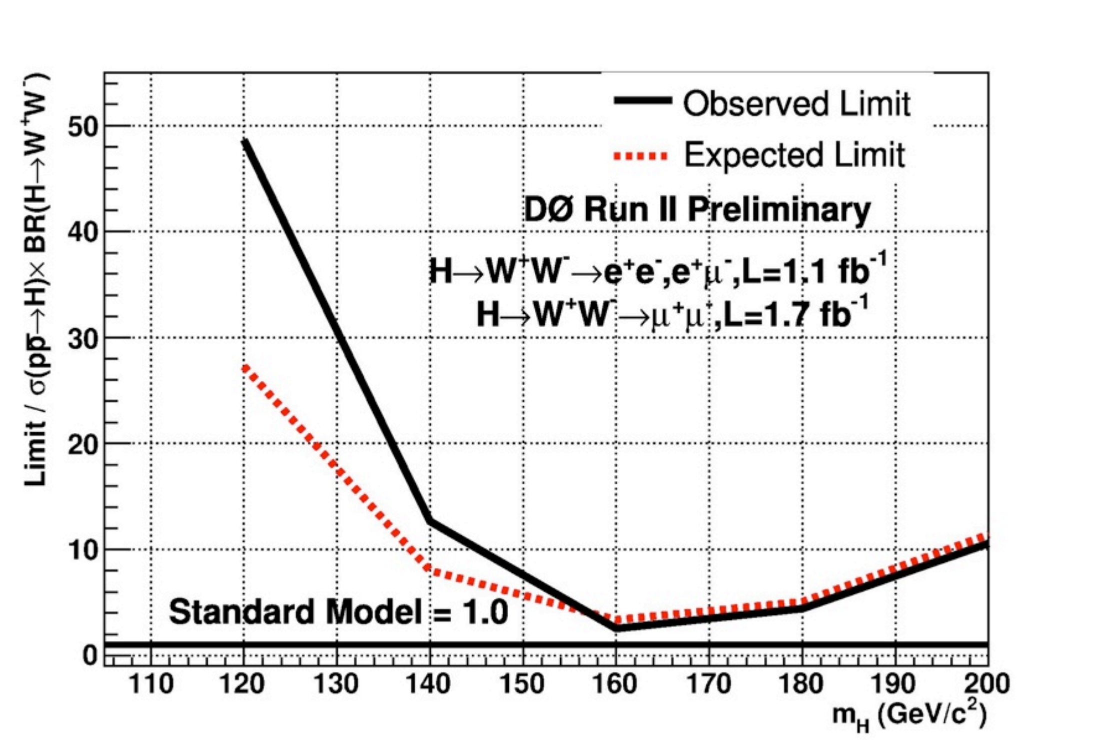
Contribution	WW	WZ	ZZ	$t\bar{t}$	DY	$W\gamma$	W+jets	H
Trigger	2	2	2	2	3	7	–	3
Lepton ID	2	1	1	2	2	1	–	2
Acceptance	6	10	10	10	6	10	–	10
$\not\!\!E_T$ Modeling	1	1	1	1	20	1	–	1
Conversions	0	0	0	0	0	20	–	0
NNLO Cross Section	10	10	10	15	5	10	–	10
PDF Uncertainty	2	3	3	2	4	2	–	2
Normalization	6	6	6	6	6	6	23	6

Contribution	Diboson	$Z/\gamma^* \to \ell\ell$	$W + jet/\gamma$	$t\bar{t}$	QCD	H
Trigger	5	5	5	5	–	5
Lepton ID	$^{+8}_{-5}$	$^{+8}_{-5}$	$^{+8}_{-5}$	$^{+8}_{-5}$	–	$^{+8}_{-5}$
Momentum resolution	2–11	2–11	2–11	2–11	–	2–11
Jet Energy Scale	10	10	10	10	–	5
Cross Section	4	4	4	4	–	4
PDF Uncertainty	4	4	4	4	–	4
Normalization	6	6	20	6	20	–

- systematic error dominated by uncertainty on background normalization
- additional significant contributions from acceptance, momentum resolution, jet energy scale

Results

- All channels, bins are used to determine combined likelihood function for best sensitivity and limit.
- Observed Limit/σ_{SM} (NNLL) = 2.4 @ m_H = 160 GeV
- Expected Limit/σ_{SM} (NNLL) = 2.8 @ m_H = 160 GeV

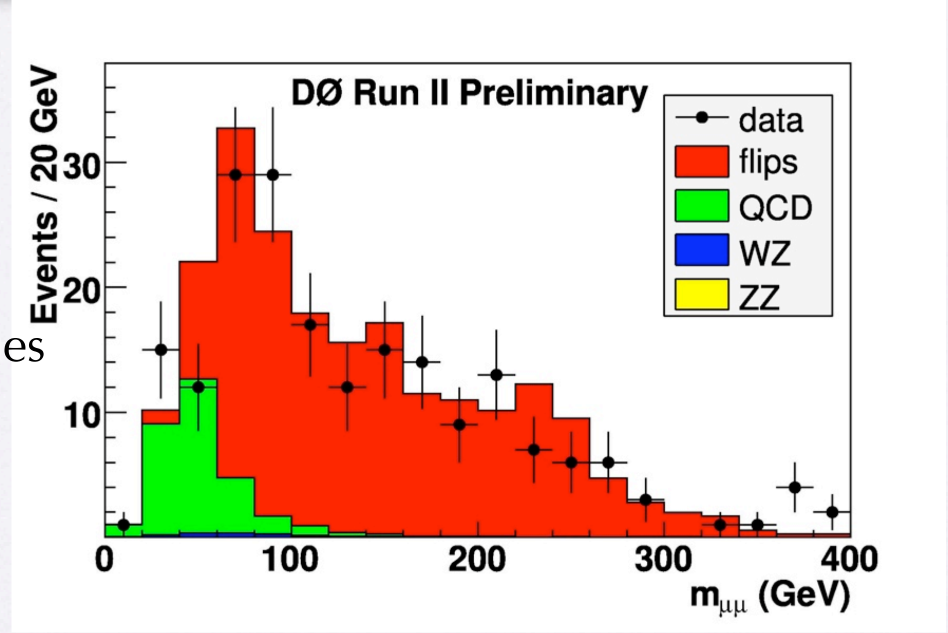


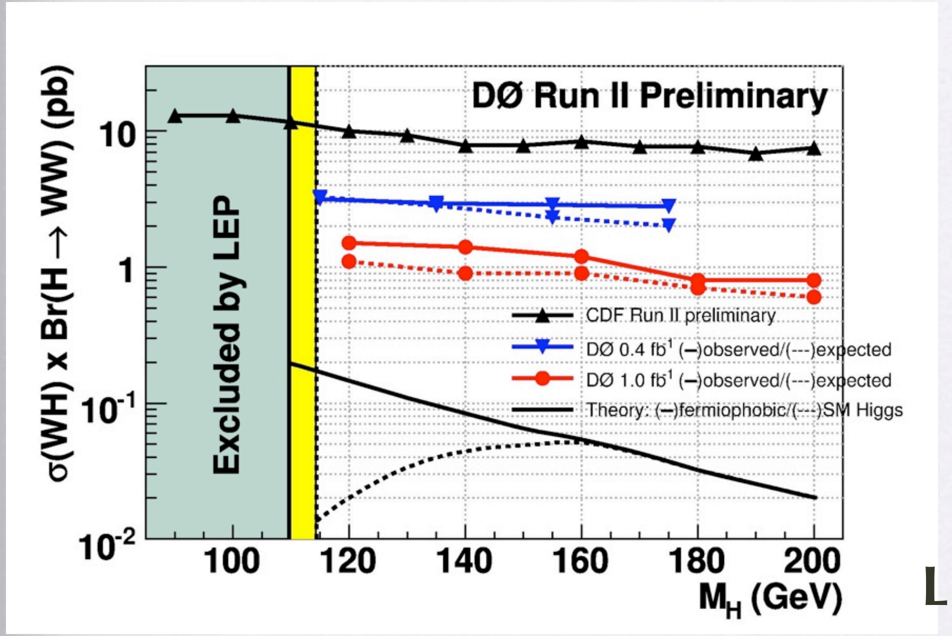
m_h [GeV]	120	140	160	180	200
	expected limit (95% C.L. limit/SM (NNLL) cross section)				
Run IIa combination (1.1 fb^{-1})	28.7	8.3	3.5	5.3	11.7
Run IIa + Run IIb combination (1.7 fb^{-1})	22.2	6.7	2.8	4.4	9.7
	observed limit (95% C.L. limit/SM (NNLL) cross section)				
Run IIa combination (1.1 fb^{-1})	48.9	12.3	3.1	5.5	11.4
Run IIa + Run IIb combination (1.7 fb^{-1})	47.3	12.0	2.4	4.7	11.1

WH->WWW*

Associated Higgs production mode makes use of like-sign isolated lepton (electrons or muons)

- one of W's from Higgs decay has same-sign lepton as associated W
- avoids large SM backgrounds (Z/γ*,WW, tt production) present in direct H→WW* searches
- background from "charge flips" accounted for by estimating flip probability from data (ratio of like to unlike sign events at high invariant mass (M_{ll}>70 GeV)





Event Selection:

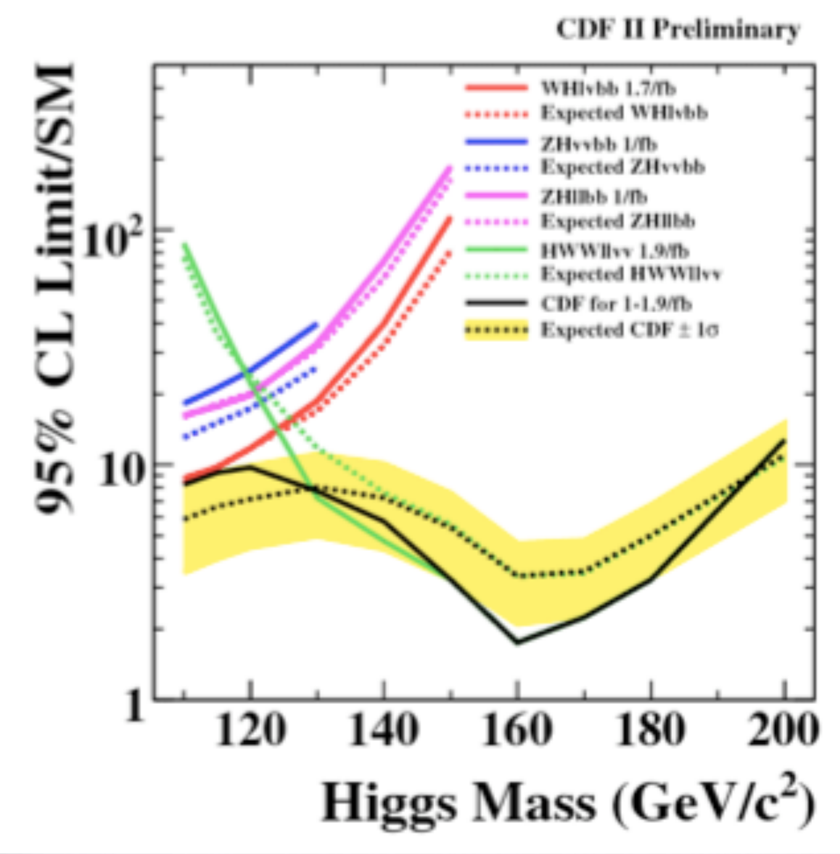
- dilepton (ee,eμ,μμ) trigger
  - EM cluster with p_T>15 GeV, $|\eta|$<1.1, matched to central track
  - isolated muon with p_T>15 GeV
- third lepton veto
- missing E_T>20 GeV

Limit: 0.9 pb at 95% CL for m_H=160 GeV

Combination Limits

- Current state-of-the-art limits on Higgs production for $m_H < 200$ GeV per experiment

CDF



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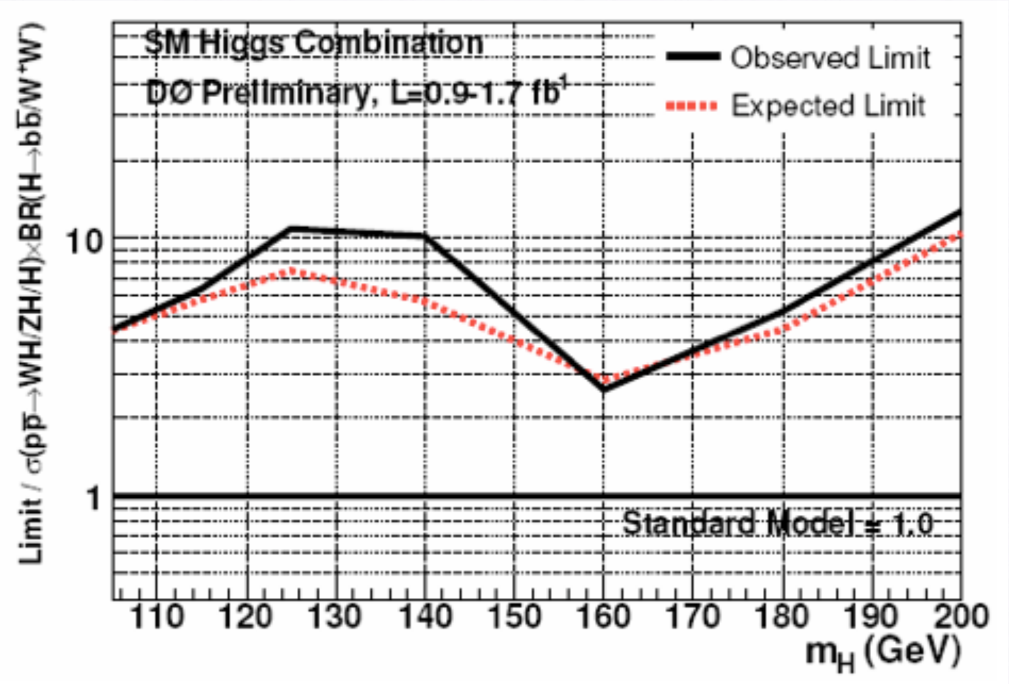
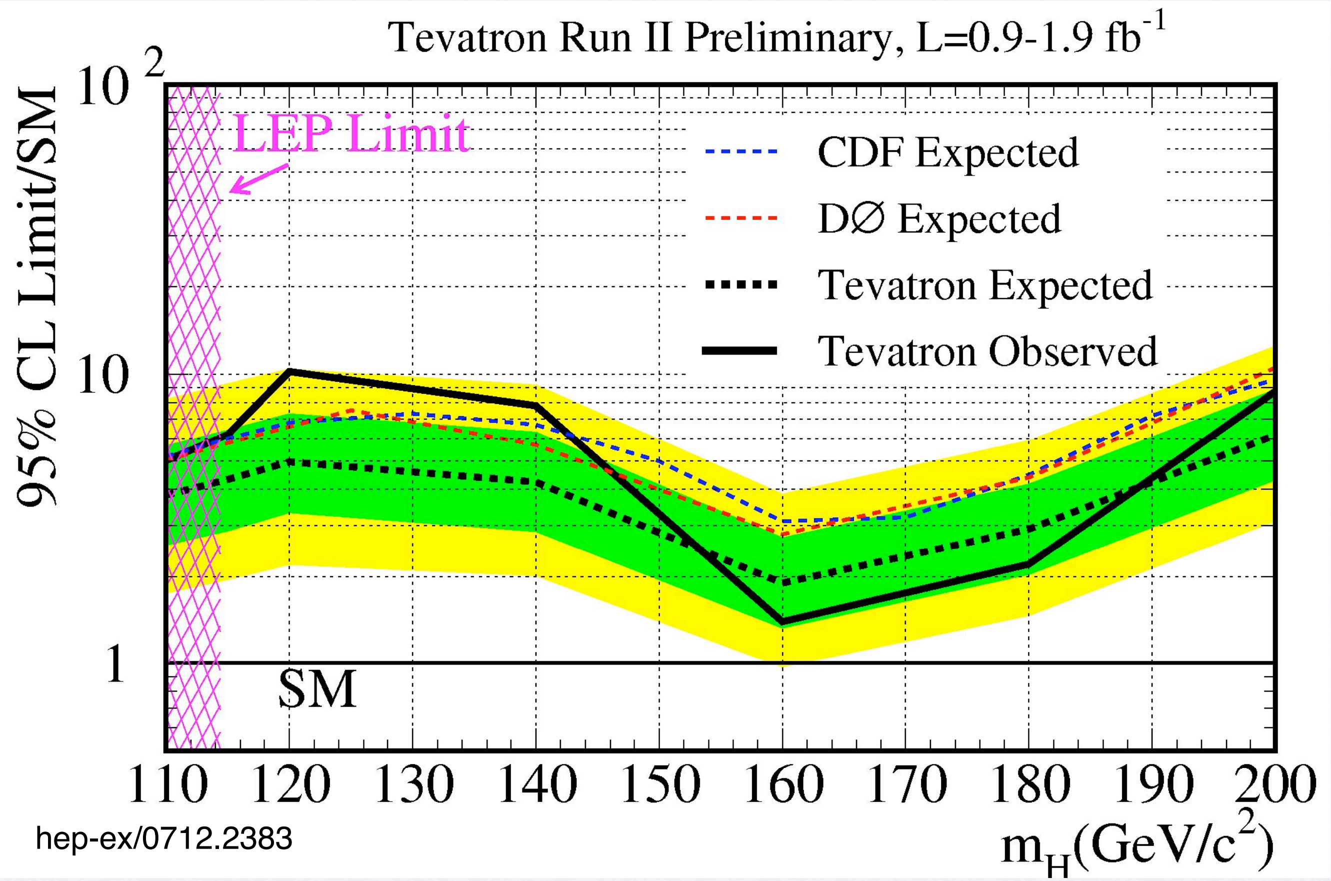


Latest Higgs Results from Tevatron

- Nearly at required sensitivity for m_H = 160 GeV! Look for tantalizing results at Moriond '08.
- D0 and CDF sensitivities are largely similar, differences can appear as each experiment updates their analyses



Expected limits:

4.3 x SM expectation at m_H=115 GeV

1.9 x SM expectation at m_H=160 GeV

Observed limit @ m_H=160 GeV - 1.4 x SM expectation

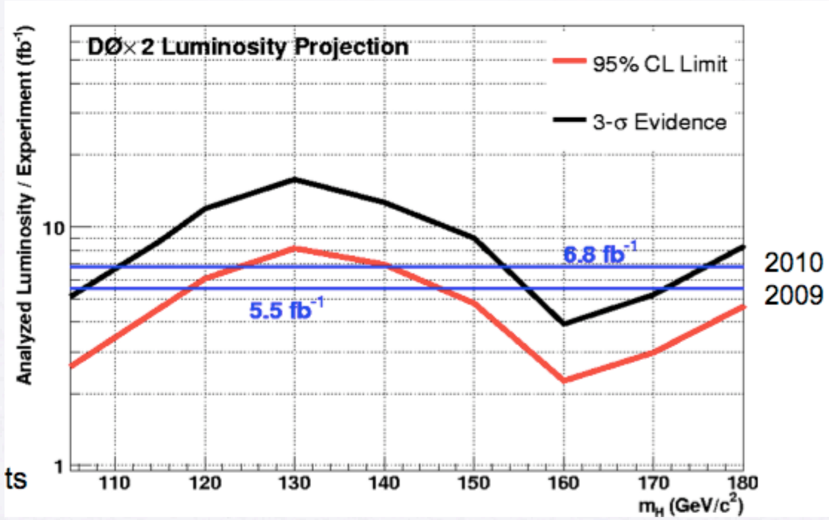
Summary and Future Prospects

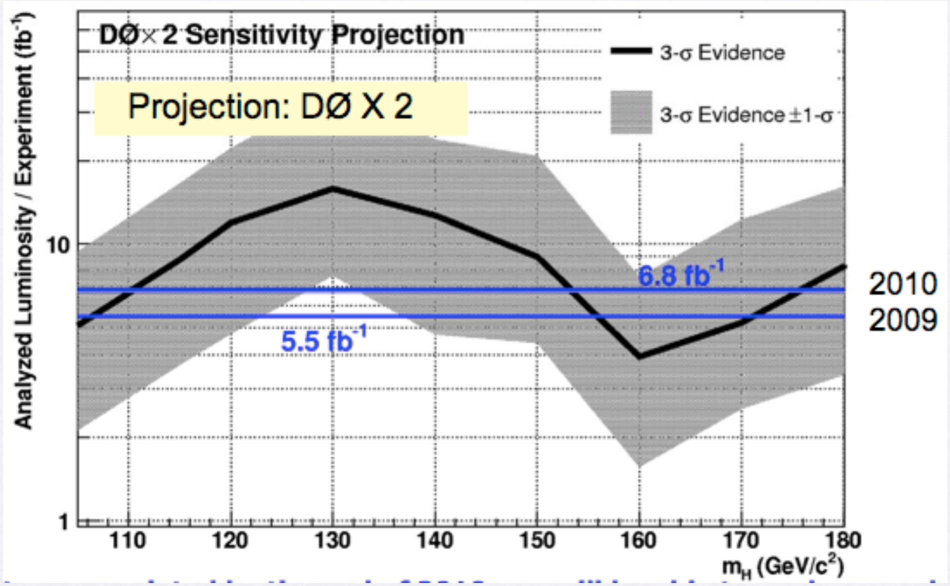
- The Tevatron is closing in on the SM at large values of Higgs mass
- CDF and D0 have comparable sensitivities
- Each experiment currently achieves expected limits of ~3 x SM cross section
- Recent improvements in NN discriminants, lepton acceptance has provided experimental sensitivity gain of 1.7 (does not include luminosity gain).
- At high mass, we expect additional gain of 1.4 from:
  - optimizing multivariate techniques (30%)
  - lepton efficiency (10%)
- Further additional improvements could come from adding tau channels

Backup

Tevatron Projections

- Including data taking efficiency, projected full data set will be
  - 5.5 fb-1 by end of 2009
  - 6.8 fb-1 by end of 2010
- Assumption: projected sensitivity for m_H = 115 GeV will be factor x2 higher than current for full dataset
  - Improvement from 2005 -> 2007 was factor 1.7
  - Several possibilities for improvement:
    - Better b-tagging with Layer 0
    - dedicated group studying dijet mass resolution
    - many gains to be made in acceptance
    - implementation of multivariate techniques
  -





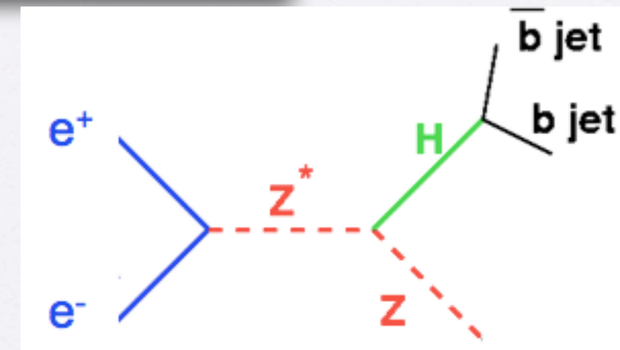
Sensitivity and Projections – M_H = 115 GeV

- Since 2005, our analysis sensitivity has improved by a factor of 1.7 beyond improvement expected from sqrt(luminosity)
  - Acceptance/kin. phase space/Trigger efficiency
  - Asymmetric tagging for double b-tags
  - b-tagging improvements (NN b-tagging)
  - improved statistical techniques/event NN discriminant
  - → for channel with largest effort applied (WH) factor was 2.1

- For 2010, we estimate that we will gain an additional factor of 2.0 beyond improvement expected from sqrt(luminosity)
  - add single-b-tag channel to $ZH \rightarrow \nu\nu bb$
  - include forward electrons, and 3-jet sample in WH
  - b-tagging improvements
    - Layer 0 (~8% per tag efficiency increase)
    - add semileptonic b-tags (~5% per tag efficiency increase)
  - Di-jet mass resolution (18% to 15% in $\sigma(m)/m$)
  - increased lepton efficiency (10% per lepton)
  - improved/additional multivariate techniques (~20% in sensitivity)

LEP Direct Searches

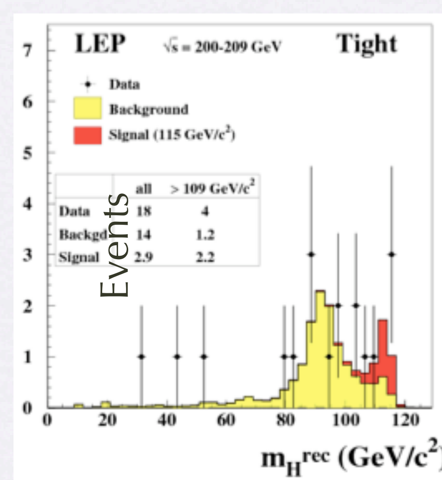
- LEP **direct search** result : combination from four experiments found hint of a signal at m_H ~118 GeV, but could be fluctuation

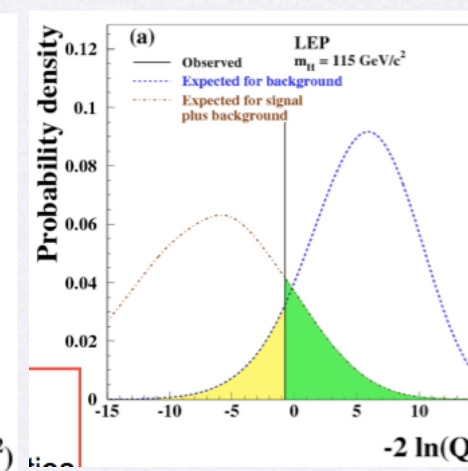


- LEP technique for deriving limits
  - Ratio of Poisson Likelihoods
  - Comparison of signal+background and background only hypotheses to data
  - Probability densities determined using toy MC experiments whose event makeup vary according to statistical and systematic uncertainties

$$\sqrt{s} - M_Z = 206.7 - 91.2 = 115.5\text{GeV}$$

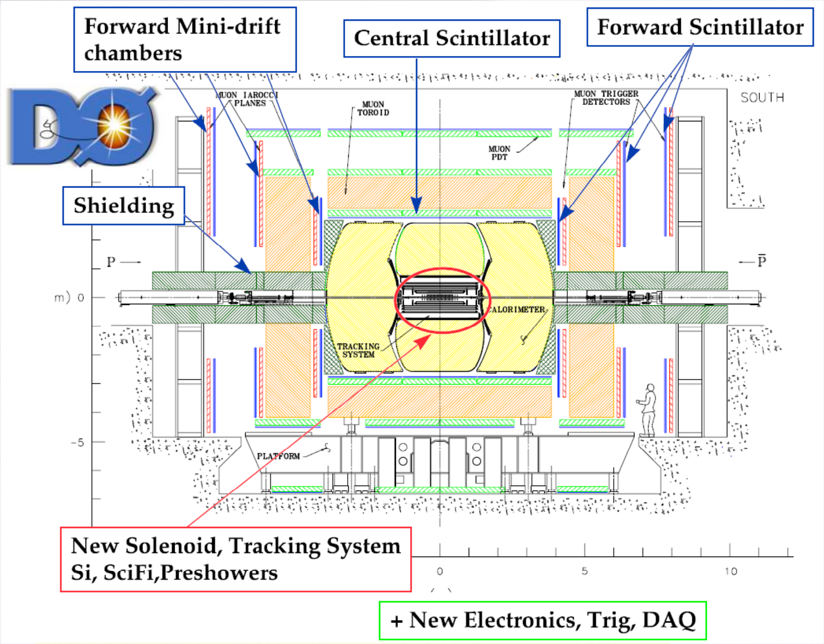
$m_H \geq 114.4$ GeV @ 95% CL

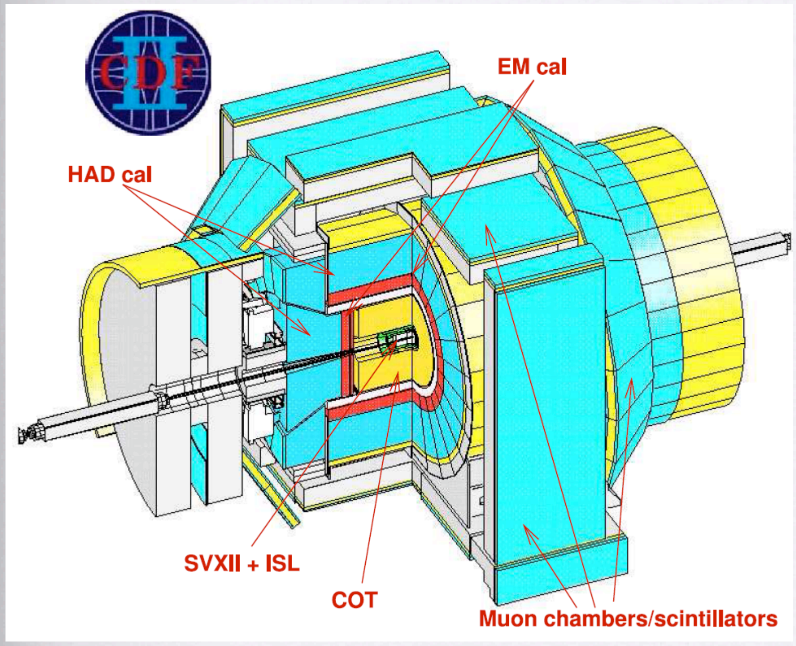




Tevatron Detectors: DØ and CDF

- DØ - Liquid Argon and Uranium Scintillator sampling calorimeter
- Silicon Microstrip and Fiber tracking
- Good muon coverage $|\eta| < 2$ $\eta = -\ln(\tan\theta/2)$
- 2T magnetic field





- CDF - Lead Scintillator sampling calorimeter
- Large tracking volume + silicon
- Muon coverage $|\eta| < 1.5$
- 1.5 T magnetic field

Event Yields

Event yields after final (stringent) selection:

	ee	eμ	μμ
lepton ID	$p_{T,1} > 15, p_{T,2} > 10, m_{ll} > 15$, isolation		
$\not{E}_T$	$\not{E}_T > 20$, significance($\not{E}_T$) > 7		
$m_{ll} < x$	$\min(m_H/2, 80)$	$m_H/2$	80
$p_{T,1} + p_{T,2} + \not{E}_T$	$m_H/2 + 20 < x < m_H$		$100 < x < 160$
$m_{T,\min}(l, \not{E}_T)$	$x > 15 + m_H/4$		$x > 55$
$H_T = \sum p_T^{\text{jet}}$	$H_T < 100$		$H_T < 70$
$\Delta\phi_{ll}$	$\Delta\phi_{ll} < 2.0$		

ee channel

M_H (GeV)	120	140	160	180	200
$H \to W^+W^-$	0.1 ± 0.005	0.41 ± 0.03	0.78 ± 0.02	0.51 ± 0.02	0.25 ± 0.01
$Z/\gamma \to ll$	0.3 ± 0.3	0.0 ± 0.0	0.0 ± 0.0	0.3 ± 0.3	0.3 ± 0.3
Diboson (WW, WZ)	7.0 ± 0.3	7.1 ± 0.3	5.5 ± 0.3	4.3 ± 0.2	5.3 ± 0.2
$t\bar{t}$	1.4 ± 0.1	1.5 ± 0.1	1.4 ± 0.1	1.2 ± 0.1	1.5 ± 0.1
W+jet/γ	5.1 ± 1.7	4.2 ± 1.5	6.7 ± 2.0	3.8 ± 1.6	5.6 ± 1.9
Multi-jet	0.2 ± 0.1	0.1 ± 0.1	0.1 ± 0.05	0.2 ± 0.1	0.15 ± 0.1
Background sum	14.1 ± 1.7	12.9 ± 1.5	13.8 ± 2.0	9.8 ± 1.6	12.9 ± 1.9
Data	12	10	15	7	11

emu channel

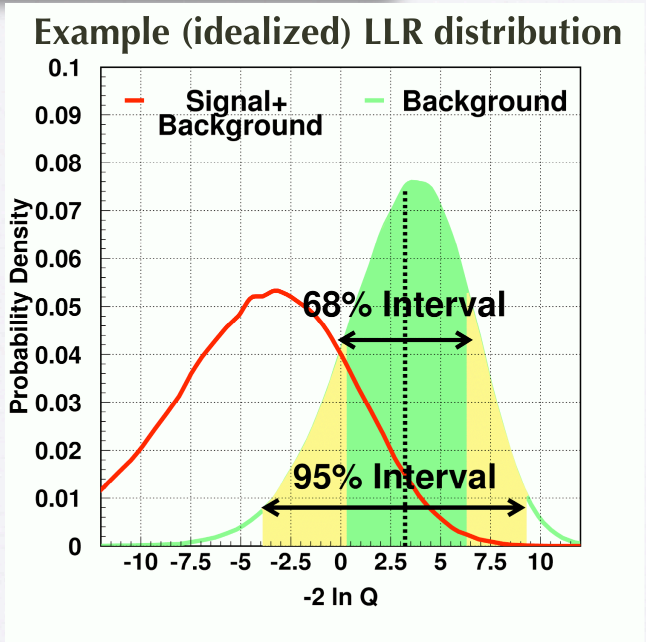
M_H (GeV)	120	140	160	180	200
$H \to W^+W^-$	0.21 ± 0.01	0.8 ± 0.02	1.64 ± 0.03	1.0 ± 0.03	0.7 ± 0.02
$Z/\gamma \to ll$	0.4 ± 0.2	0.2 ± 0.1	0.2 ± 0.1	0.1 ± 0.1	0.2 ± 0.1
Diboson (WW, WZ)	14.6 ± 0.1	14.2 ± 0.1	13.2 ± 0.1	10.3 ± 0.1	19.3 ± 0.1
$t\bar{t}$	1.1 ± 0.1	1.1 ± 0.1	1.25 ± 0.1	1.1 ± 0.1	1.9 ± 0.1
W+jet/γ	5.5 ± 1.5	4.8 ± 1.4	7.5 ± 1.9	5.5 ± 1.6	9.9 ± 2.2
Multi-jet	1.3 ± 0.2	0.9 ± 0.2	2.1 ± 0.2	0.9 ± 0.2	1.0 ± 0.2
Background sum	23.0 ± 1.6	21.3 ± 1.5	24.2 ± 2.0	17.8 ± 1.6	32.0 ± 2.3
Data	25	20	20	14	28

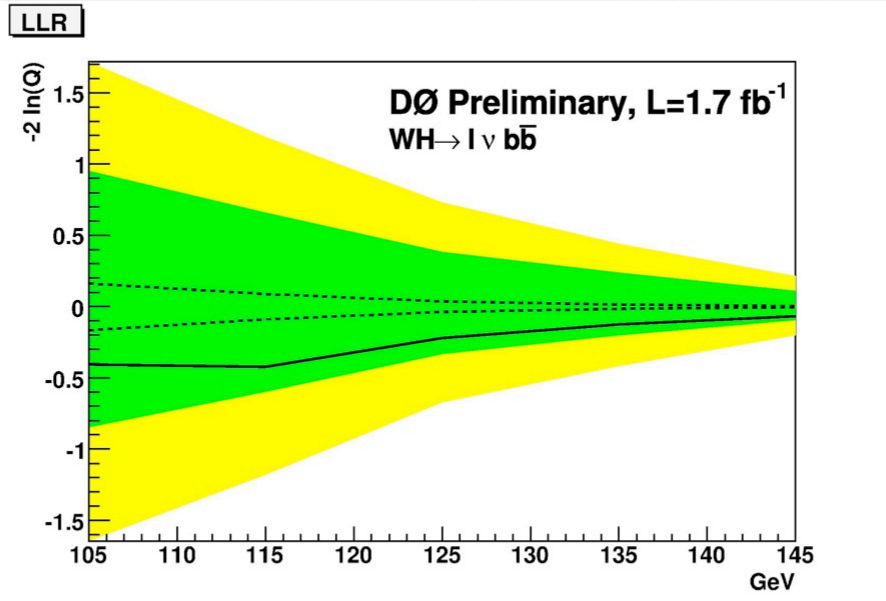
mumu channel

M_H (GeV)	120	140	160	180	200
$H \to W^+W^-$	0.32 ± 0.01	0.87 ± 0.01	1.29 ± 0.01	0.90 ± 0.03	0.43 ± 0.01
$Z/\gamma \to ll$	9.4 ± 0.6	6.0 ± 0.5	1.3 ± 0.2	1.5 ± 0.2	2.9 ± 0.3
Diboson (WW, WZ)	12.5 ± 0.1	14.9 ± 0.1	9.7 ± 0.1	10.7 ± 0.1	14.7 ± 0.1
$t\bar{t}$	0.4 ± 0.1	0.8 ± 0.1	0.6 ± 0.1	0.7 ± 0.1	0.7 ± 0.1
W+jet/γ	8.0 ± 1.7	3.5 ± 1.1	1.1 ± 1.1	1.0 ± 1.1	0 ± 1.7
Multi-jet	0.2 ± 0.1	0.1 ± 0.1	$0. \pm 0.$	$0. \pm 0.$	0 ± 0
Background sum	20.8 ± 1.7	25.3 ± 1.2	12.6 ± 2.0	13.8 ± 1.2	18.3 ± 1.7
Data	31	24	10	12	18

Deriving Limits

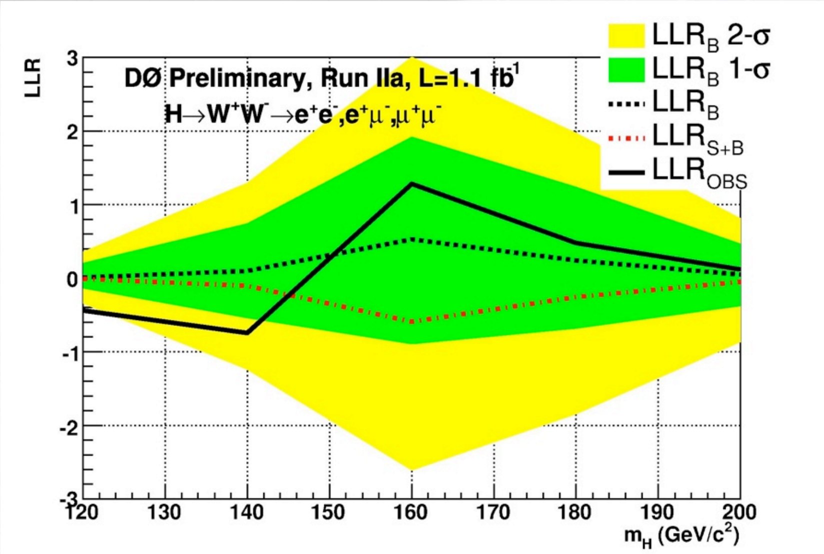
- Limits derived using semi-frequentist CL_s method where test statistic is LLR = -2LogQ = -2Log[P(s+b)/P(b)]
  - P are probability distribution functions for the signal+background and background only hypotheses
  - P are populated via random Poisson trials with mean values given by the expected number of events in each hypothesis.
  - Systematic uncertainties are incorporated by varying the expected number of events in each hypothesis according to the size and correlations of the uncertainties





Results

Limits derived using semi-frequentist CL_s method where test statistic is
LLR = -2LogQ = -2Log[P(s+b)/P(b)]

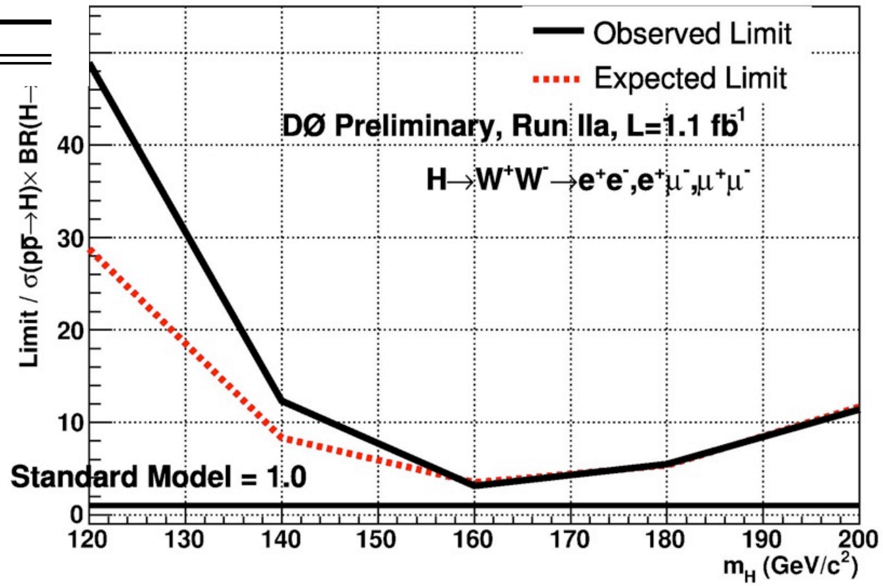


Limit per channel:

M_H, [GeV]	120	140	160	180	200
	expected limit (95% C.L. limit/SM (NNLL) cross section)				
ee	59.1	16.6	7.65	11.5	26.7
$e\mu$	39.9	10.7	5.0	7.2	14.8
$\mu\mu$	48.2	16.9	8.5	13.6	32.2
Run IIa combination	28.7	8.3	3.5	5.3	11.7
	observed limit (95% C.L. limit/SM (NNLL) cross section)				
ee	80.8	19.4	8.0	12.6	21.9
$e\mu$	66.3	14.9	3.7	5.7	15.7
$\mu\mu$	56.3	22.0	11.3	20.0	33.2
Run IIa combination	48.9	12.3	3.1	5.5	11.4

- All channels, bins are used to determine combined LLR for best sensitivity and limit:

m_h [GeV]	120	140	160	180	200
	expected limit (95% C.L. limit/SM (NNLL) cross section)				
Run IIa combination (1.1 fb^{-1})	28.7	8.3	3.5	5.3	11.7
Run IIa + Run IIb combination (1.7 fb^{-1})	22.2	6.7	2.8	4.4	9.7
	observed limit (95% C.L. limit/SM (NNLL) cross section)				
Run IIa combination (1.1 fb^{-1})	48.9	12.3	3.1	5.5	11.4
Run IIa + Run IIb combination (1.7 fb^{-1})	47.3	12.0	2.4	4.7	11.1

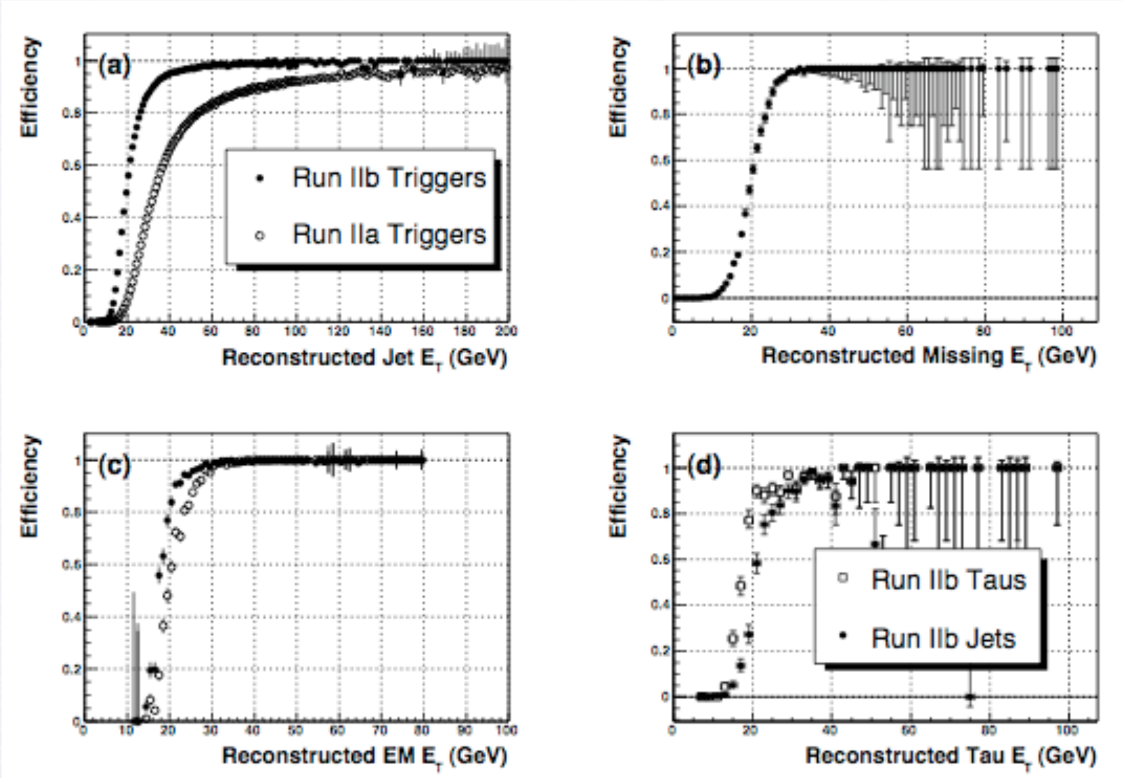


L1Cal2b Upgrade

- Upgraded trigger electronics provide better digitization and allows for sophisticated hardware (sliding window) algorithms including clustering at Level 1.

- New features include triggers for jets, taus, isolated electrons, missing E_T, and topological triggers, e.g. acoplanar jets or back-to-back electrons

Improved L1Cal2b algorithms allows us to run at higher instantaneous luminosity with no degradation (enhancement in some cases) in trigger efficiency



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